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Core Curriculum

The basics of hemodialysis equipment

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INTRODUCTION

The hemodialysis (HD) machine pumps the dialysate as well as the patient's blood through a dialyzer. The blood and dialysate are separated from each other by a semipermeable membrane permitting solute and water transfer as governed by laws of physics. In practice, however, this procedure is somewhat more complex. The operational system of the HD machine represents a complex array of detectors, controllers, monitors, and safety devices to ensure a safe operation. This integrated system allows the operator the ability to control the blood and the dialysate circuits as well as monitor important variables like ultrafiltration (UF) rate, adequacy, dialysate composition, and circuit pressures. Although such advances make patient management somewhat easier for the nephrologist, they do not change the basic tenet of patient care—first to do no harm. Consequently, it is extremely important for the practicing nephrologist to recognize and understand the terminology, significance, and management of the basic operational mechanics of HD machines. This article will focus on essential principles of HD equipment that are necessary for ensuring a safe, standard HD procedure (the description of equipment for other specialized procedures like hemofiltration is beyond the scope of this review).

From a practical point of view, it is often useful to divide the HD process into two main parts, that is, the blood circuit and the dialysate circuit. The standards for HD equipment in the United States are set by the AAMI (Association for the Advancement of Medical Instrumentation).

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GENERAL GUIDELINES GOVERNING THE USE OF HD EQUIPMENT

Know your machine! Patient safety is the most important goal that should never be compromised.

Various "alarms" built into the system can signal impending or ongoing system malfunction. Alarms should never be taken lightly and disarming of alarms should never be practiced. The range and sensitivity of the alarms should be internally set as default and the operator should only be able to operate within the set range without being able to alter these settings, especially while HD is in progress. Alarms should be not only visible (2 m) but also easily audible (70 dB). All blood alarms [air detector, arterial, venous, blood leak, transmembrane pressure (TMP), blood pump torque] should automatically shut off the blood pump, clamp the venous return line, and stop UF, thus isolating the patient. Equipment is programmed to automatically switch to "safe mode," thus essentially isolating the patient from the HD machine. This does not correct the operational characteristics that set off the alarm in the first place, however. Properly trained nurses who take active (and proactive) action to correct the malfunction are always the ultimate backup to ensure safety.

THE BLOOD CIRCUIT (FIG. 1)

The blood circuit (Fig. 1A) consists of the following components:

- Pressure monitors (arterial, prepump; and venous, postdialyzer);
- Blood tubing;
- Blood pump;
- Heparin pump;
- Air leak detector; and
- Clamps.

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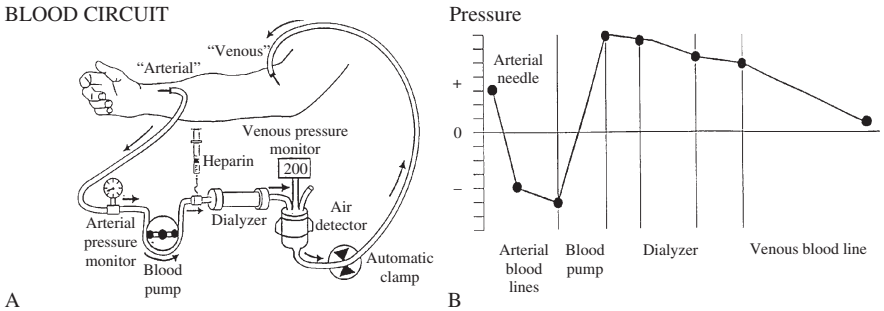

Figure 1 (A) The blood circuit. (B) The pressure profile in the blood circuit with an arteriovenous fistula as the blood access. (If a central venous access is used, the pressure profile will reflect the central venous pressures that are close to 0 or even slightly negative.) Reprinted by permission of Mayo Foundation for Medical Education and Research. All rights reserved.

Arterial pressure monitor (prepump)

This component monitors the pressure between the blood access and the blood pump. The pressure is negative between the access and the blood pump (Fig. 1B) but achieves a high positive range post-blood pump (Fig. 1B). The pressure transducer signal is amplified and converted to an electrical signal. Alarms may indicate patient disconnection, separation of blood tubing, or obstruction/kink in the blood circuit. The normal pressure reading in this segment of the blood circuit is negative (subatmospheric). Negative pressure makes this segment prone to entry of air into the bloodstream. Longer needles with smaller bores increase negative pressure readings in this segment. Likewise, negative-pressure augmentation may be seen when longer catheters with smaller internal diameter bores are used, especially with higher blood flows. Out-of-range pressures trigger the machine to clamp the blood line and activate the appropriate alarms.

Causes of low arterial pressure alarm

- Fall in blood pressure;
- Kink between needle and pump;
- Clot (check for air bubbles); and
- Suction of vessel wall into the needle.

Causes of a high arterial pressure alarm

- Increase in patient's blood pressure;
- Circuit disruption between access and pump;
- Unclamping of saline infusion line; and
- Blood pump that has torn the pumping segment (check for blood leak).

Venous pressure monitor (postdialyer)

The venous pressure may build up owing to resistance to venous return anywhere between the venous drip chamber and the venous needle (together with the access pressure). Venous pressure monitors normally read positive pressures. Out-of-range pressures trigger clamping of the blood line, stopping of the blood pump, and activation of appropriate alarms, with shutting of the venous return.

Causes of a low venous pressure alarm

- Disruption of connections anywhere downstream from the blood pump to and including the venous needle and access; and
- Low blood flow (upstream of blood pump).

Causes of a high venous pressure alarm (high venous pressure may rupture the dialyzer membrane!)

- Kink in the venous return line;
- Clot in the venous drip chamber; and
- Venous access malfunction.

Blood tubing

Blood tubing is made of biocompatible and nontoxic material. The blood tubing in the pump segment is treated with silicone to minimize blood clotting. Because of its high cost, the use of silicone-treated blood tubing in single-use systems is uncommon. Leaching of phthalate di-(2-ethylhexyl) phthalate (DEHP) from polyvinyl chloride (PVC), a constituent of the blood tubing, may occur into the blood circulation and lead to liver damage. Phthalate may very rarely lead to anaphylaxis.

Blood pump

Blood is pumped in the circuit by peristaltic action at a rate of 200 to 600 mL/min. The pump usually has two rollers (roller rotation compresses the tubing, thus forcing blood along the tube), operating on a low-voltage motor (less electrical hazard). The blood pump is spring-loaded to prevent under-/overocclusion of the blood tubing (the pump segment of the tubing is made up of thicker and more resilient material). The pump is adaptable to different sized tubing if indicated clinically and can be operated manually in the event of a power loss. It is calibrated to measure blood flow rate (BFR) depending on the internal diameter of the tubing:

$$\text{BFR} = \text{rpm (measured directly)} \times \text{tubing volume } (\text{Pi} \times r^2 \times 1),$$

where r is the internal radius of the tubing and l is the length of the tubing being compressed between the two rollers. Owing to limited rigidity, the tubing between the two rollers flattens with a high negative pressure and the above formula overestimates the blood flow at high BFR.

Heparin pump

The heparin pump is commonly a syringe pump, although a roller pump may be used. Heparin is infused downstream into the positive-pressure segment of the blood circuit (post-blood pump, predialyzer). If infused prepump in the negative-pressure segment, the risk of air embolism is enhanced.

Air leak detector

The air leak detector is one of the most important features of a HD machine. It is placed distally in the venous blood line and monitors for and prevents air embolus (incidence of major air embolus is approximately in 1:2000 treatments). The usual volume of air needed to result in this complication is 60 to 125 mL (1 mL/kg/min, may vary), especially if rapidly injected. The air presents as foam with microbubbles.

Likely points of air entry

- Arterial needle;
- Prepump arterial tubing segment;
- Open venous catheter; and
- Empty bags and infusion sets.

Requirements for air detector

- Should preferably be ultrasound (US)-based (detects change in US frequency caused by air foam).
- Should respond to air in blood, blood and saline, or saline alone. Because fluids transmit sound more efficiently, a drop in the intensity of US indicates presence of air bubbles (rate of transmission of US: blood > saline > air).
- Must activate alarm and stop pump.
- Must activate venous line clamp capable of complete occlusion of blood return line to 800 mmHg (high-compliance dialyzers will "squeeze" blood into the blood circuit even with the pump stopped).
- Should not be oversensitive (to prevent unnecessary alarms).

Blood tubing clamps

The blood tubing clamps should be able to withstand pressures up to 800 mmHg. They should automatically shut if the circuit is broken or electrical power is lost (it should be possible to open them manually if power is lost).

THE DIALYSATE CIRCUIT (FIG. 2)

Present-day machines employ single-pass systems that discard the spent dialysate once it circulates through the dialyzer. The delivery of safe dialysate involves careful regulation of its temperature, concentration, flow, pressure, as well as its proper disinfection and/or cleaning. The key components/processes of this circuit include:

- Heating;
- Deaeration;
- Proportioning;
- Monitoring;
- UF; and
- Disinfection;

The mixing (proportioning) of the dialysate and bicarbonate with pure water may be done by individual machines or centrally. In the latter instance, the premixed dialysate is then delivered to individual dialysis machines.

Heating of the dialysate

In most machines, heating increases the temperature of the incoming water (not the dialysate) to body temperature and degasses cold water. It also improves mixing

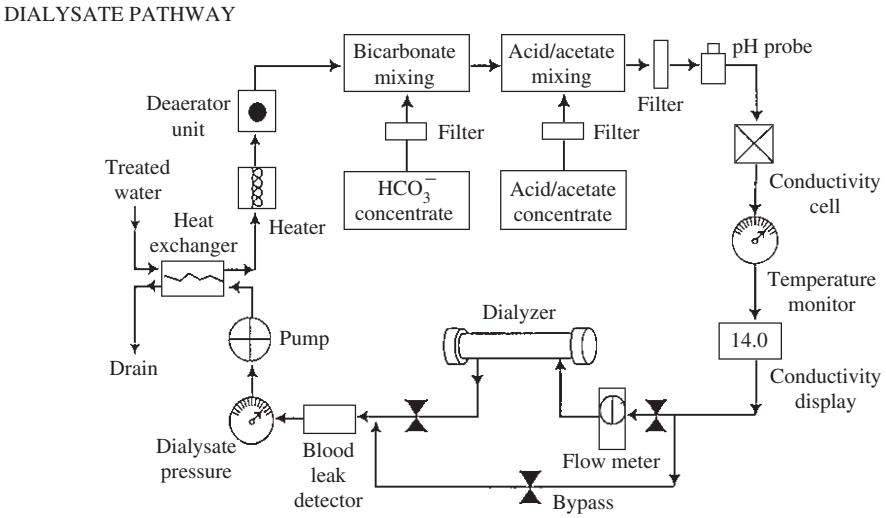

Figure 2 The dialysate circuit. Reprinted by permission of Mayo Foundation for Medical Education and Research. All rights reserved.

with the dialysate concentrate. Its heating elements need to be made of stainless steel (not copper or aluminum). Internal controls (preset) should limit the temperature range to 33 to 39°C (92–102°F). This function is monitored downstream by the dialysate temperature control monitor in the dialysate circuit.

Dialysate deaeration

Deaeration (degassing) prevents potential problems caused by air dissolved in the water of the dialysate solution. Air may cause flow problems in the dialyzer (air locking). It may also cause alterations in UF by affecting the TMP in addition to affecting the function of various monitors. Water is heated to physiologic temperatures and then subjected to negative pressure, thus venting any released air. The negative pressure is achieved by a "constricting valve" situated upstream of the pump that circulates water in a closed loop containing an air trap and vent (Fig. 3). Alternatively, deaeration may be accomplished by heating the water to 85°C followed by cooling before proportioning.

Dialysate proportioning

Dialysate proportioning ensures proper mixing of heated and treated water with one or more streams of dialysate concentrate (see later) to prepare a dialysate of correct proportion, temperature, and conductivity within specific physiologic limits. This is accomplished by means of proportioning pumps and concentrates:

- Acid-chloride salts of Na, K, Ca, Mg, and acetate; and
- Bicarbonate-sodium bicarbonate and sodium chloride.

Bicarbonate is made fresh, because preprepared bicarbonate may slowly release CO_2 into the air and supports bacterial growth.

Potential proportioning problems

- Wrong concentrate [**note color coding of lines, red-acid, and blue-base**—different concentration attributed to different manufacturers (Fresenius acid 34:1, Cobe acid 44:1)];
- Poor mixing;
- Clogged filters;
- Crystallization in the system; and
- Human disarming of switches.

Electrolyte abnormalities attributed to proportioning problems

- High or low plasma sodium;
- High or low plasma osmolality;
- High or low plasma potassium; and
- High calcium/magnesium.

Clinical problems related to dialysate water

- Hemolysis (copper may leach from cuprophane or from the heating element. Currently, cuprophane

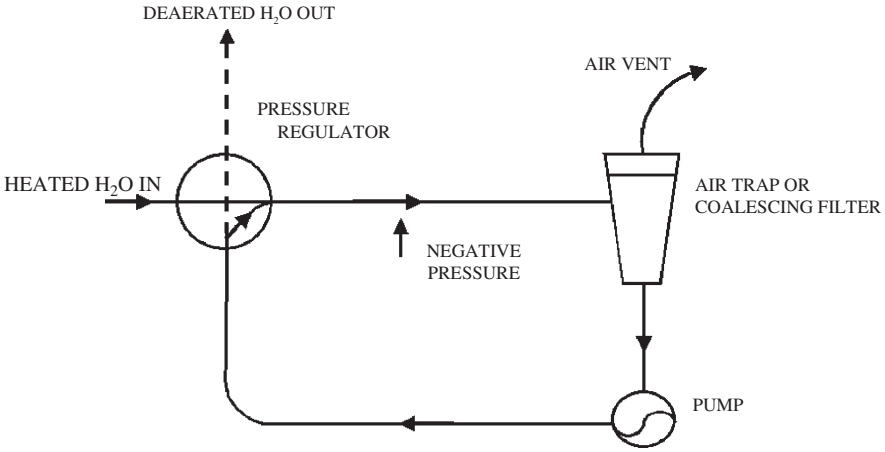

Figure 3 Dialysate deaeration. Copyrighted material, Monash University (www.ecse.monash.edu.au/ucourses/ECE 3802).

dialyzers are sparingly used in the developed world and heating elements are made of stainless steel).
- Hemolysis (nitrates and chloramine).
- Ventricular tachycardia, pruritus (although fluoride has not been a constituent of water for the past two to three decades).

Monitoring of the dialysate circuit

pH

This monitors the ratio of HCO_3^- to H_2CO_3 (pH) of the dialysate. The recommended pH range is 6.8 to 7.6. Not all machines come equipped with a pH monitor.

Temperature monitor

The temperature monitor is a heat sensor that monitors the dialysate temperature near the dialyzer; it should have a short feedback loop to the heater element to allow quick adjustment of the temperature (± 0.5°C). The usual recommended temperature range is 35 to 42°C. Colder dialysate temperatures are used to prevent hypotensive episodes during HD. When the monitor alarms, the dialysate is automatically diverted to the drain.

- Cold dialysate may cause shivering.
- Warm dialysate (>42°C) may cause protein denaturation.
- Warmer dialysate (>45°C) may cause hemolysis.

Conductivity

The conductivity monitors must be made of high-quality corrosion resistant material. The ionic constituents of the dialysate determine its conductivity. Conductivity monitoring ensures proper water:concentrate ratio of the dialysate. The units of conductivity are millisiemens per centimeter. The normal range is 12 to 16 mS/cm; high and low alarm settings should be within $\pm 5\%$ of the sensitivity settings. **External readjustment of the alarm settings by machine operators can lead to extremely risky and dangerous situations.** Conductivity can be affected by temperature or acetate:chloride or chloride:-bicarbonate ratio.

Measurement of conductivity

The conductivity sensor consists of two metal electrodes that are exactly 1 cm apart and protrude into water. A constant voltage is applied between the two electrodes. An electrical current flows through the water owing to this voltage and is proportional to the concentration of the dissolved ions in the water—the greater the number of ions, the more conductive the water (or lesser the resistance/impedance), resulting in a higher current that is measured electronically. Because the electrical current flow increases with increasing temperature, the electrical conductivity values are automatically corrected to a standard value of 25°C. The values are then technically referred to as specific electrical conductivity. The conductivity output signal is adjusted for temperature changes by an attached thermistor (Fig. 4). It is mandatory to regularly check the functioning of conductivity meters by formal analysis of the dialysate sodium concentration (e.g., by direct or indirect ion-selective electrode method or by flame photometry. Unfortunately, these methods too, are subject to a high error rate owing to problems with standardization). The alarm

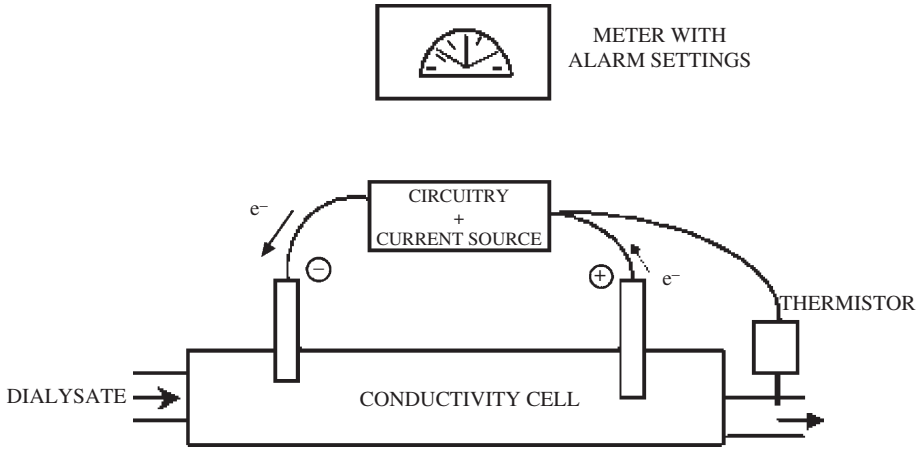

Figure 4 Dialysate conductivity measurement. Copyrighted material, Monash University (www.ecse.monash.edu.au/ucourses/ECE 3802).

points should be such that they cannot be changed. (sodium 120–160 m eq/L)

Management of dialysate alarms
Alarms should interrupt the supply of dialysate to the dialyzer: **check for "no flow" in the flow meter and no dialysate stream at the dialyzer:**

- Is the concentrate container empty?
- Is the concentrate line connector plugged in?
- Is the water inlet pressure normal?
- Are there any water leaks and/or puddles beneath the mixing chambers?

Never adjust conductivity settings while the patient is connected to the dialysis machine!

Dialysate pressure, pump, and UF control

Dialysate pressure is monitored similar to monitoring of pressure in the blood circuit.

Pressure monitors
The pressure range is −400 to +350 mmHg with an accuracy ± 10%; alarm limits are set at ± 10% of the pressure setting. Dialysate side positive pressure should not exceed blood compartment pressure (risk of blood contamination by unsterile dialysate following membrane rupture and backfiltration). Some backfiltration, however, is common with high blood flow rates and dialyzers with long fiber length. UF is controlled by TMP. $TMP = P_{BO} - P_{DO}$ (the pressure difference at the blood and dialysate outlets). TMP is adjusted to achieve the desired rate of UF, as low as 50 mL/hr. Modern volumetric dialysis machines achieve the desired UF based on flow sensor systems (inflow and outflow) that measure the pre- and postdialyzer flow rates (the difference is the UF rate) (Fig. 5A) or by matching the dialysate inflow and outflow rates (a separate pump is available for UF) (Fig. 5B). By keeping the pumps out of sequence, the dialysate keeps flowing continuously.

Blood leak monitoring
The blood leak monitor allows detection of blood leaks and prevention of dialysate contamination by blood downstream of the dialyzer. The monitor (infrared or photo detector) has a "flow-through" configuration (sensor is at the bottom, and therefore, air bubbles do not interfere) (Fig. 6). Red blood cells present in the dialysate scatter light. The monitor operates by looking for loss of transparency when light is passed through the dialysate column (postdialyzer). Loss of sensitivity may occur owing to biofilm, deposits, or clots. The sensitivity of monitor is 0.25 of 0.35 mL of blood per liter of dialysate. Monitor triggers visual and audible alarms, immediately deactivating blood pump.

Dialysate disinfection and rinsing

All parts of the dialysate circuit should be exposed to the disinfectant. Adequate time for disinfection ensures adequate bacterial killing. The machine should be in bypass mode during disinfection with dialysate alarms overridden. The blood pump power supply should be off as a safeguard. The effluent dialysate line should be isolated from the drain with an air break to prevent backflow and siphoning. Heat during disinfection might caramelize

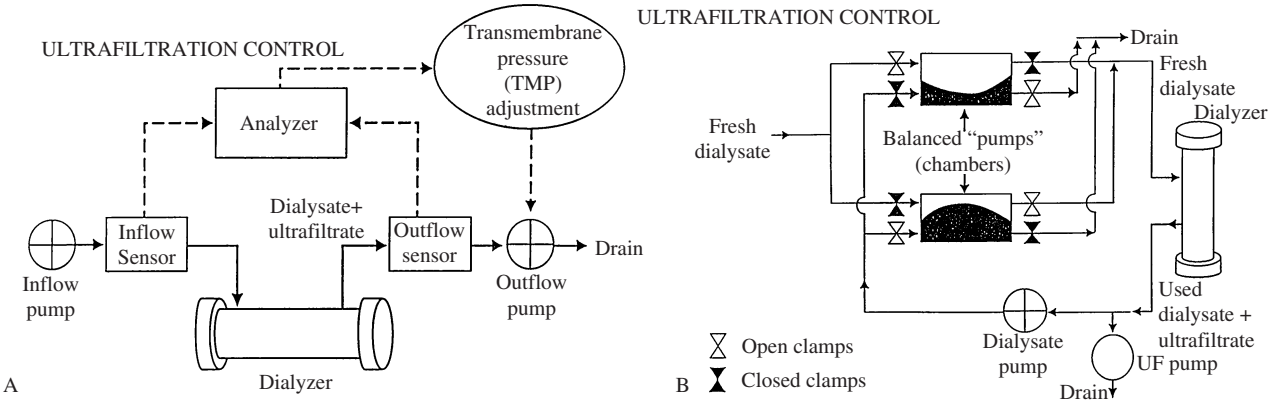

Figure 5 Ultrafiltration: (A) flow sensor–based; (B) volumetric balancing–based. Reprinted by permission of Mayo Foundation for Medical Education and Research. All rights reserved.

dextrose causing malfunction of blood leak detectors and obstruction of valves.

Dialyzer disinfectants and rinse solutions
Dialyzer disinfectants and rinse solutions include formaldehyde, hypochlorite (bleach), and peracetic acid.

- Always rinse the machine between chemicals.
- Always rinse the machine before a dialysis session.
- Always run a detection test before dialysis to test for residual chemicals.
- Always disinfect reused bicarbonate/acid containers.

Possible sources of endotoxin/bacterial contamination of final dialysate

- Contaminated water;
- Back siphon from the drain;
- Dead space in the system;
- Inadequate disinfection; and
- Bicarbonate concentrate (aqueous).

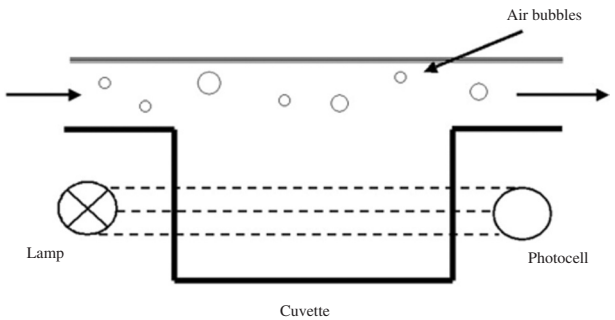

Figure 6 Blood leak monitor. Copyrighted material, Monash University (www.ecse.monash.edu.au/ucourses/ECE 3802).

Power failure

The battery sets off an alarm on the machine. Remember that all systems and monitors are now OFF. The system is no longer FAILSAFE. Do not pump blood from patient into the system. Recirculate blood manually for a maximum of 15 to 30 min. The venous clamp should be disconnected to return the blood through the venous line. Heparin should be introduced manually.

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